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Scenarios for a hierarchical assessment of the global sustainability of electric power plants in México

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ABSTRACT

Today, there are indicators to assess the sustainable development of a country and the energetic sector in general, but not to assess electric power plants. This work is aimed at evaluating the sustainability of specific technological systems. A multi-criteria method called Analytical Hierarchization Process was applied to analyze sustainability throughout the life cycle of various electric power plants in México (such as hydroelectric, coal, heavy oil thermoelectric, natural gas thermoelectric, geothermal, nuclear, wind energy, photothermal and photovoltaic plants). An analysis throughout the whole life cycle makes it easier to assess and prepare an inventory of all sustainability indicators, resulting in a useful report for decision-making purposes in order to drive sustainable development in the electric sector. Four scenarios were analyzed using information provided by the Comisión Federal de Electricidad (*Electric Power Federal Commission*), the opinion of experts, and scenarios with ecological and technocrat tendencies. The global result, using the measure of central tendency, reflects the benefit of renewable energies: wind energy is the most sustainable energy under the current circumstances of our country.

Contents

1. Introduction

In 1972, the Club of Rome published a report on the limitations of energy resources, and the fact that they would be depleted in the long term was already evident. Such report was titled *Limits to*

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Growth [1]. In addition to this warning, the first energy crises emerged, making evident the extent to which the world growth and the economic model for development relied on the ongoing energy consumption. As a consequence, many countries implemented various actions: energy saving and efficiency policies; exploitation of alternate sources; industrial reconversion; use of new materials and waste recycling; among others.

As a result, in 1987, the UN World Commission on Environment and Development [2] unanimously approved the document "Our Common Future," or Brundtland Report, the most comprehensive agreement between scientists and politicians all over the world, which summarizes the global challenges we are facing at an environmental level with respect to sustainable development. Sustainable development was defined as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs, with special concern for equality within each generation" [3]. In 1997, México adopted the program of action for achieving sustainable development, or Agenda 21, whereby it agreed to take both national and global steps in favor of sustainability [4], and steps aimed at generating sustainable development indicators [5].

During the Earth Summit in Rio de Janeiro, in 1992, and the Kyoto Summit in 1997, efforts were made to reach an agreement with respect to the vital importance of the energy-related aspect of climate changes. The European Union has also recognized that there is an urgent need to deal with the issue of greenhouse gas emissions, identifying a series of areas where action is required in the form of energy policies, including the strengthening of the fundamental role of renewable energy sources [6].

The technological dimension of sustainable development emphasizes the need for a change towards cleaner and more efficient technologies, as close to zero emissions as possible that minimizes consumption of energy and other natural resources. However, fossil fuels supply about 95% of the energy used for commercial purposes worldwide and the use of these fuels is increasing at an approximate rate of 20% per decade [7] that make necessary to evaluate the viability of power stations around the sustainable concept. The use of fossil fuels, an example of an open industrial process, is one of the main sources of urban air pollution; acid rain affecting broad areas and greenhouse gases that cause climate changes. Therefore, in order to achieve sustainable development, we need to use less fossil fuels and find others safe and accessible [7].

Technologies producing world problems such as global warming and, at a local level, emissions by electric power plants, should be analyzed from a sustainable point of view. Since, burning fossil fuels generates 75% of the causing gases of greenhouse effect of the global warming.

Combustion of conventional fuels to generate electricity is one of the main causes of global warming.

In order to offer a method that facilitates decision making with respect to the convenience of using a particular electricity-generating technology, taking into account sustainability, all dimensions of sustainability shall be examined (social, institutional, environmental and economic); therefore, the Analytical Hierarchization Process (AHP) was used because it delivers a list of options, ranked from the best one to the worst one [8].

The Life Cycle Analysis (LCA) also allows to study the sustainability of energetic systems by examining all processes, raw materials and energy flows, from extraction, transformation and use, and their final return to the ecosystem, when they are removed; the economic, social, institutional and environmental points of view are included [9].

Preliminary results, in the operation stage of 5 electric plants of Comisión Federal de Electricidad (CFE), using real data, showed that wind energy technology is more sustainable than technologies using conventional energy sources [10]. Another preliminary study, throughout the life cycle of nine facilities, using two scenarios with an ecological and technocrat bias, showed that, according to the ecological scenario, the most sustainable facility is the hydroelectric plant, and according to the technocrat scenario, the most sustainable facility is the one using nuclear energy [10].

This work shows an assessment of global sustainability throughout the life cycle of nine electric power plants in Mexico, in four scenarios and in an integral way.

2. Analytical Hierarchization Process

Saaty established an analytical hierarchy [11]. His method was chosen because it provides a comprehensive problem-solving framework, a systematic procedure for representing the elements of any problem. It allows us to organize the basic facts by breaking down a problem into smaller parts, which may be compared pairwise. This method does not require consistent judgments. The degree of consistency of the judgments becomes apparent at the end of the process. The basic law of hierarchic decomposition requires elements in the next higher level; the objective is to derive priorities for the elements in the last level that reflect, as well as possible, their relative impact on the structure of the hierarchy. The principle of comparative judgments calls for setting up a matrix to carry out pairwise comparisons of the relative importance of elements in the second level with respect to the overall objective of the first level. The process of comparing elements in each level is continued through the hierarchy. From pairwise comparison, matrices for local priorities are generated. They express the impact of a set of elements on an element in the level immediately above. The scale used in making judgments is 1 for equal importance, 3 for moderate importance, 5 for strong importance, 7 for very strong importance, and 9 for extreme importance. If activity i has a number assigned to it when compared with activity j, then j has the reciprocal value when compared to i [12].

AHP is a tool that facilitates decision-making considering multiple criteria, allowing [10]

(a) to make a judgment about the relative importance of plants, decomposing the problem and structuring its elements according to a hierarchical order,
(b) make comparative judgments of the components; and
(c) prepare a summary of comparisons in order to obtain final priorities, and to have a final judgment as objective as possible.

It is almost impossible to compare all plants at the same time, and the AHP method offers the advantage of pairwise comparison.

Saaty designed this scale, made up of nine elements, to appropriately and sufficiently reflect the various degrees or levels of discrimination or intensity assigned by a person to the relationship between a given set of elements. Also this method considers that each comparison, and therefore each measurement, resulting from this technique, falls in the same scale, so they are adjusted to the principle of homogenization of the measurement theory, particularly when working with really diverse and varied factors or variables [9].

3. Life Cycle Analysis

The sustainable production concept is essentially aimed at achieving the highest possible technical, environmental, economic and institutional efficiency at each stage of the life cycle [13].

Improving production systems through technologies and processes that use resources more efficiently and, at the same time,

produce less waste (achieve more using less), is an important means to make power plants sustainable.

According to ISO 14040:1997 [14], LCA is a technique to determine the environmental aspects and potential impact associated with a product, and it is carried out by keeping an inventory of the relevant inputs and outputs of the system, evaluating the potential environmental impact associated to such inputs and outputs, and interpreting the results of the inventory and impact phases with respect to the purposes of the study. This methodology considers a series or interconnected work phases, following a more or less defined sequence, although sometimes it is possible to perform a less broad analysis by obviating one phase. According to ISO 14040, LCA is structured into four phases: goal and scope definition; inventory analysis; impact assessment; and interpretation of results. This work considered all four phases: goal (sustainability); analysis of sustainability indicators; assessment of sustainability indicators and interpretation of results.

4. Assessment of environment indicators

Environment indicators were ranked using Espinoza's environmental impact evaluation method [15]:

$$In = C\frac{(P+I+O+E+D+R)}{54} \tag{1}$$

where *In* is the environment indicator, defined as the result of multiplying character (*C*, permissible limit according to Mexican Official Standards) by the sum of six environment criteria, divided by 54, the result of adding up all criteria when assigned a mark of 9; *C* is character; *P* is disturbance; *I* is importance; *O* is occurrence; *E* is extension; *D* is duration; and *R* is reversibility.

In this equation, seven criteria are ranked according to a scale of impact levels, depending on the degree to which the assessed criterion is affected: 1 for scarce or low effects; and 9 for the strongest effect.

5. Methodology

For the evaluation of the sustainability in each stage and for the whole life cycle of power plants, selected for the Mexican context, based in the document of sustainable development indicators for México [5] and the document of sustainable development indicators for the energy sector [16], the following methodology was developed:

(i) Based on the document of 134 sustainable development indicators in México, by INEGI [5], contributing to both raise awareness of the sustainability problem and to support the design of sustainable development strategies and policies in our country, divided in four dimensions of sustainability: economic; social; environmental and institutional; as well as the list of indicators of the International Atomic Energy Agency (IAEA) developed to assess the progress towards the goal of achieving a sustainable development of the energy sector [16]. Twelve indicators were selected for the study of electric power plants, as shown in Fig. 1, grouped by dimension: 4 economic indicators; 2 social indicators; 2 institutional indicators; and 4 environment indicators.

(ii) Plants were selected by type of fuel, seven currently operated by the CFE and two solar plants analyzed in the context of considered scenarios. Such plants have the following characteristics: four thermoelectric (natural gas, heavy oil, coal and nuclear energy); wind energy; hydroelectric; and one geothermal.

(iii) From environmental impact studies that were requested to the library of the Department of the Environment and Natural Resources, environment indicators were assessed for electric power plants operated by the CFE; for solar plants, information was generated through implicit opinion bias in the proposed scenarios. Studies of environmental impact are required by law for the installation, operation and decommission of any electric power plant. The ranking for each environment indicator was recorded in an Excel spreadsheet, using a Leopold matrix [15]. With the information of the environmental impact studies, various criteria were assessed at each stage of the life cycle, for each analyzed plant. Results were grouped by indicator in the four environmental subjects, obtaining four indicators per plant: air; water; soil; and biodiversity. Environment indicators received a mark according to Espinoza's environmental impact evaluation method [15].

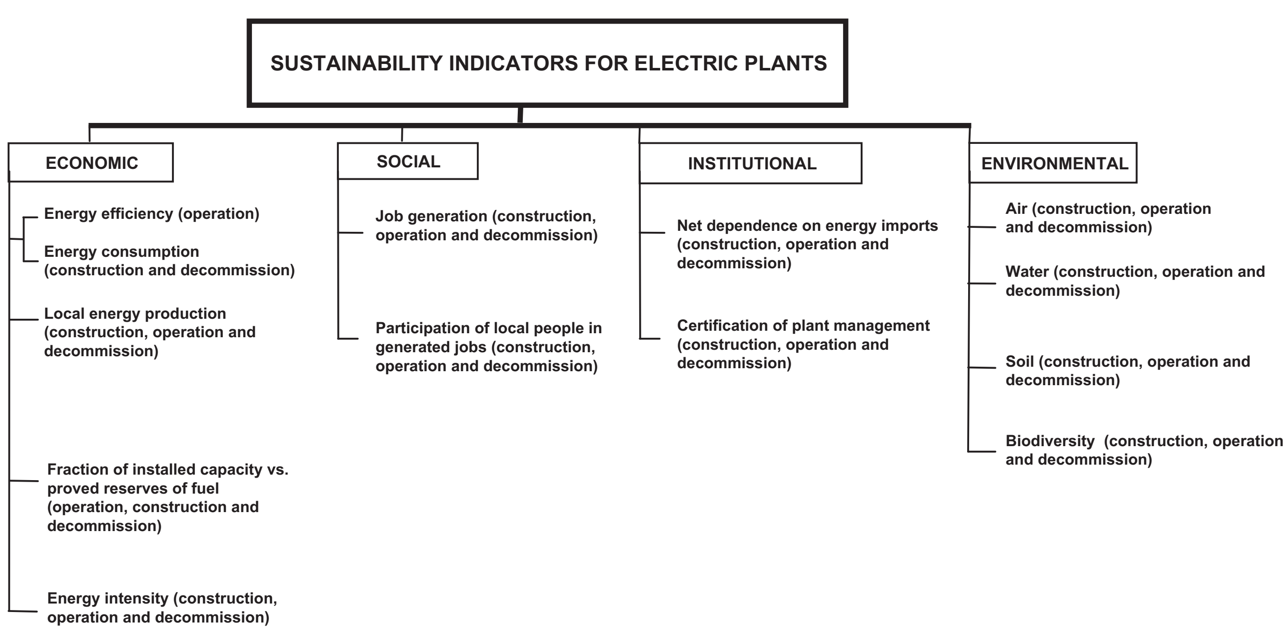

Fig. 1. Sustainability indicators for electric plants during their whole life cycle.

(iv) Four scenarios were proposed to assess the sustainability of electric power plants, formed by three information sources: CFE technical data; assessment with ecological and technocrat biases and expert opinions. The scenarios were classified and formed this way, for the lack of technical data of the 9 power plants. The indicators for these 4 scenarios were generated as follows:
- In the ecological scenario for the whole life cycle, authors responded subjectively, evaluators had completely biased opinions towards environment preservation with respect to other issues such as economic, social or technological issues.
- In the technocrat scenario for the whole life cycle, authors assessed without regard to environmental or social aspects.
- In the slightly ecological scenario, for operation and decommission stages through expert opinion, a questionnaire was sent to approximately dozens of persons closely related to the energy and environmental sector of our country; they were asked to assess using Saaty's scale, based on their own biased opinion, sustainability indicators for both stages. For the stage of operation through technical data provided by CFE and finally, to assess both solar plants, information provided by the ecological scenario throughout the whole life cycle of both plants was used.
- In the slightly technocrat scenario, for the operation and decommission stages through expert opinion, a questionnaire was sent to approximately dozens of persons closely related to the energy and environmental sector of our country, asking them to assess using Saaty's scale, based on their own biased opinion, sustainability indicators for both stages. For the stage of operation through technical data provided by CFE, and finally, to assess both solar plants, information provided by the technocrat scenario throughout the whole life cycle of both plants is used.

(v) A sustainability assessment for the whole life cycle of each plant was conducted, following the steps of each process, energy flows and raw materials, from its extraction, transformation and use, to its return to the ecosystem.

(vi) For the hierarchization of selected electricity-generating plants, the basic scale created by Saaty [11] was used: 12 indicators for the 9 plants during the 3 stages of the life cycle for each scenario were ranked. All indicators were assessed: 1, for intensity equal to or different from…; 2, for intensity slightly more significant than…; 5, more significant than…; and 9 absolutely much more significant than …

To compare the different plants with respect to their sustainability, the Web Hipre software of the Technological University of Helsinki was used [17], which gives as final output a hierarchical order of all plants, indicating both the best and the worst option. By designing a hierarchy tree, the AHP makes it possible to establish and analyze the links between, at least, three levels: goal; assessment criteria; and options. In this case, the purpose is to achieve sustainability, criteria are divided in three sublevels by life cycle stage, sustainability area and sustainability indicator, and the options are the analyzed electric power plants. All elements, connected by lines, shall be compared pairwise in order to determine their relative importance. A partial view of this structure can be seen in Fig. 2.

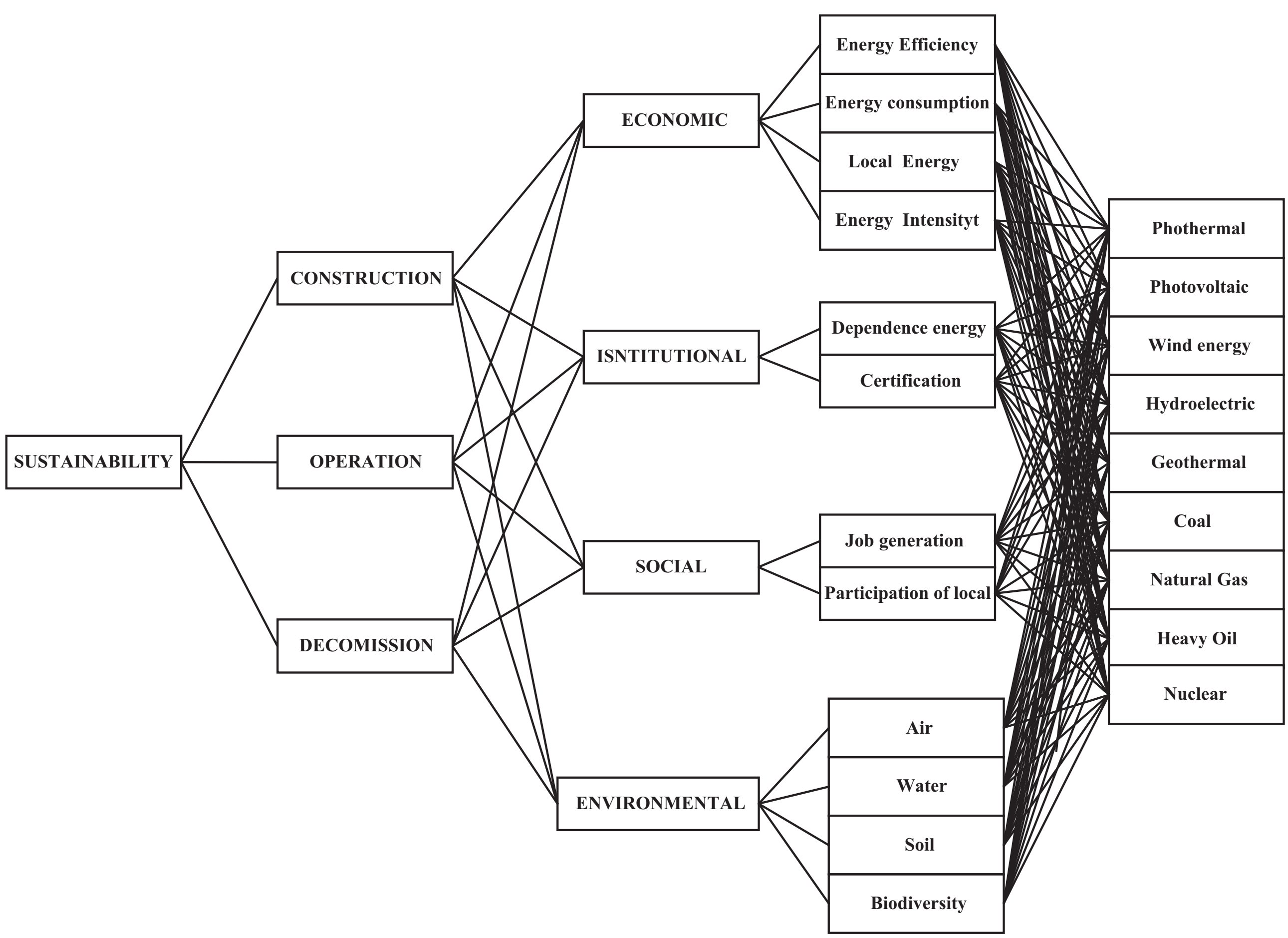

Fig. 2. Hierarchy tree for the sustainability assessment of electric power plants, from general objective (sustainability) to three levels of criteria, and to options (electric plants).

A sensitivity analysis was performed to test the results from all scenarios, again using Web Hipre software, which presents results graphically. Any variation in a parameter normalized between 0.00 and 1.00 shows how the hierarchy of options may or may not vary. Such analysis was conducted for each hierarchical level of the analyzed problem.

(vii) The results of hierarchical sustainability were grouped and ordered in upward form without caring the type of power plant; then the numeric value of the median was identified. When the numeric value of the median of a database is different to the average, then its distribution has a bias. For this reason, to define a parameter of global sustainability, the median was used as statistical tool and it was proposed that the plants with larger values that the median were sustainable than others. The use of the median value will allow a direct comparison among the different alternatives in the four scenarios, and help to define which is the most relevant power plant, in this study: the most sustainable. This approach has been used in other areas where the valuations depend on circumstances. In particular, it has been used successfully in scientometrics when comparing the factor of impact of the magazines to define the out standings in a specific of category [18].

Then, the following criteria were chosen to evaluate global sustainability:

(1) values over the median are considered acceptable;
(2) values below the median are considered unacceptable; and
(3) the result is considered property sustainable if it is found at least in 50% of the scenarios.

6. Results and discussion

6.1. Environment indicators

For each analyzed power plant (hydroelectric, coal, thermoelectric-heavy oil, thermoelectric-natural gas, geothermal, nuclear and wind energy), global environment indicators were obtained by environmental subject and by life cycle stage. The values of such indicators, as shown in Table 1, indicate that:

(A) During the construction stage, the least affected environmental subject in all plants was air, and the most affected, biodiversity.
(B) During the stage of operation for hydroelectric, nuclear and wind energy plants, the least affected environmental subject was air; for all coal, natural gas, heavy oil and geothermal plants, it was water. And, the most affected environmental subjects were air and biodiversity.
(C) During the decommission stage, environmental subjects showing only a slight modification, in the hydroelectric plant were soil and biodiversity, and in nuclear, natural gas, heavy oil and geothermal plants, it was water. For nuclear, heavy oil and geothermal plants, it was water. Normally, at this stage, there are modifications benefiting environmental subjects, due to restoration works at site, re-potentiation, etc.

6.2. Hierarchization of electricity-generating plants

6.2.1. Ecological scenario

In this scenario, the hierarchical result of global sustainability for electric power plants by fuel type was hydroelectric, photothermal, wind energy, photovoltaic, geothermal, natural gas, heavy oil, coal and nuclear. Also, intermediate results by dimension are (see Table 3): from an economic point of view, wind energy is better; from the social point of view, hydroelectric plants are better; from an institutional point of view, a photothermal plant is better; and from an environmental point of view, wind energy technology is better.

6.2.2. Slightly ecological scenario

The hierarchy for sustainability throughout the life cycle of electricity-generating plants, as shown in Table 2 is photovoltaic, photothermal, wind energy, hydroelectric and, finally, plants using conventional fuels; according to the sustainability concept, they reflect the unquestionable participation of renewable technologies in sustainable development. Also, intermediate results by dimension are as shown in Table 3; results both economically and institutionally, photothermal technology is the most sustainable; socially, nuclear and coal technologies are the most sustainable, and environmentally and institutionally, photothermal technology is the most sustainable.

Sustainability results by life cycle stage for each plant show that, during the construction stage, the hydroelectric plant is the most sustainable, whereas during the operation stage, wind energy and hydroelectric plants are the most sustainable ones and, finally, during the decommission stage, the hydroelectric plant is deemed the most sustainable, as can be seen in Table 4.

6.2.3. Technocrat scenario

The sustainability hierarchy is as follows: nuclear; coal; heavy oil; natural gas; geothermal; photovoltaic; wind energy; photothermal; and hydroelectric, as shown in Table 2. Also, intermediate results by

Table 1
Results for environment indicators by life-cycle stage and environmental subject for each analyzed electric power plant, using the Espinoza method.

	Hydro	Coal	Nuclear	Natural gas	Heavy fuel oil	Geothermal	Wind energy
C							
Water	−0.04	−0.05	−0.05	−0.05	−0.05	−0.026	0.00
Soil	−0.24	−0.19	−0.19	0.19	−0.19	−0.187	−0.21
Biodiversity	−0.40	−0.40	−0.40	−0.40	−0.40	−0.324	−0.35
Air	0.00	0.00	0.00	0.00	0.00	0.000	0.00
O							
Water	−0.10	−0.09	−0.07	−0.08	−0.09	−0.069	0.00
Soil	−0.17	−0.20	−0.42	−0.15	−0.17	−0.146	−0.1
Biodiversity	−0.22	−0.11	−0.56	−0.09	−0.11	0.440	−0.07
Air	−0.05	−0.37	0.00	−0.31	−0.24	0.131	−0.00
D							
Water	0.00	−0.07	0.07	−0.07	−0.07	−0.070	0.00
Soil	−0.01	0.05	0.05	0.05	0.05	0.041	0.08
Biodiversity	−0.21	0.21	0.21	0.21	0.21	0.210	0.21
Air	0.00	0.00	0.00	0.00	0.00	0.000	0.00

C=construction, O=operation, D=decommission.

Table 2
Global sustainability values by scenario for each electric power plant.

Slightly ecological scenario		**Slightly technocrat scenario**		**Ecological scenario**		Technocrat scenario	
Plant	**S**	**Plant**	**S**	**Plant**	**S**	**Plant**	**S**
Photovoltaic	0.21	Wind energy	0.18	Hydroelectric	0.28	Nuclear	0.25
Photothermal	0.18	Hydroelectric	0.16	Photothermal	0.28	Coal	0.18
Wind energy	0.14	Geothermal	0.12	Wind energy	0.18	Heavy fuel oil	0.12
Hydroelectric	0.1	Natural gas	0.11	Photovoltaic	0.13	Natural gas	0.11
Natural gas	0.08	Heavy fuel oil	0.10	Geothermal	0.02	Geothermal	0.10
Geothermal	0.08	Coal	0.1	Heavy fuel oil	0.04	Photovoltaic	0.06
Heavy fuel oil	0.07	Nuclear	0.08	Coal	0.04	Wind energy	0.06
Nuclear	0.07	Photovoltaic	0.08	Natural Gas	0.03	Photothermal	0.06
Coal	0.07	Photothermal	0.07	Nuclear	0.03	Hydroelectric	0.06

Table 3
Sustainability values by dimension and scenario for each electric power plant.

Dimension	**Economic**				**Social**				**Environmental**				**Institutional**			
Scenario Plant	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Hydroelectric	0.06	0.06	0.09	0.01	0.06	0.06	0.09	0.01	0.10	0.11	0.05	0.01	0.15	0.15	0.09	0.01
Coal	0.05	0.05	0.01	0.05	0.05	0.06	0.01	0.03	0.41	0.10	0.07	0.05	0.07	0.07	0.00	0.05
Wind energy	0.04	0.04	0.04	0.02	0.04	0.54	0.03	0.02	0.18	0.14	0.07	0.01	0.15	0.15	0.06	0.01
Natural gas	0.14	0.14	0.01	0.03	0.14	0.06	0.02	0.02	0.11	0.1	0.01	0.03	0.07	0.07	0.01	0.03
Heavy oil	0.03	0.13	0.01	0.02	0.13	0.06	0.01	0.02	0.11	0.09	0.1	0.04	0.05	0.05	0.01	0.03
Geothermal	0.14	0.03	0.03	0.02	0.03	0.01	0.01	0.04	0.1	0.15	0.02	0.02	0.15	0.15	0.01	0.03
Nuclear	0.21	0.14	0.01	0.08	0.14	0.14	0.01	0.09	0.12	0.11	0.01	0.07	0.03	0.03	0.01	0.04
Photovoltaic	0.21	0.21	0.03	0.02	0.21	0	0.02	0.02	0.1	0.1	0.04	0.01	0.16	0.16	0.02	0.02
Photothermal	0.22	0.22	0.03	0.02	0.22	0	0.04	0.02	0.1	0.1	0.04	0.01	0.16	0.16	0.04	0.02

1 = slightly ecological, 2 = slightly technocrat, 3 = ecological, 4 = technocrat.

Table 4
Sustainability results by life-cycle stage and scenario, for each electric power plant.

Stage	**Construction**				**Operation**				**Decommission**			
Scenario Plant	1	2	3	4	1	2	3	4	1	2	3	4
Hydroelectric	0.09	0.19	0.09	0.06	0.09	0.1	0.09	0.28	0.12	0.19	0.09	0.06
Coal	0.06	0.11	0.01	0.17	0.07	0.07	0.05	0.19	0.07	0.12	0.05	0.18
Wind energy	0.08	0.16	0.06	0.07	0.23	0.22	0.07	0.11	0.11	0.17	0.07	0.07
Natural gas	0.08	0.15	0.01	0.11	0.05	0.09	0.05	0.12	0.07	0.09	0.05	0.11
Heavy oil	0.07	0.1	0.01	0.11	0.09	0.08	0.03	0.1	0.07	0.12	0.03	0.12
Geothermal	0.07	0.12	0.03	0.11	0.09	0.09	0.01	0.06	0.08	0.14	0.01	0.11
Nuclear	0.06	0.07	0.01	0.24	0.11	0.11	0.01	0.06	0.05	0.07	0.01	0.25
Photovoltaic	0.29	0.05	0.05	0.07	0.12	0.11	0.01	0.06	0.24	0.06	0.01	0.06
Photothermal	0.20	0.05	0.06	0.06	0.11	0.12	0.01	0.04	0.21	0.05	0.01	0.06

1 = slightly ecological, 2 = slightly technocrat, 3 = ecological, 4 = technocrat.

dimension are: from an economic, environmental and institutional point of view, nuclear technology is the best one; from a social point of view, nuclear technology is the most sustainable.

6.2.4. Slightly technocrat scenario

The hierarchy for the technocrat scenario is: wind energy; hydroelectric; geothermal; heavy oil; coal; nuclear; and finally, solar; by dimension, results are: economically and institutionally, photothermal technology is the most sustainable; socially, wind energy technology; and environmentally, geothermal technology.

6.2.5. Global hierarchization of all scenarios

Using the median method and taking into account sustainability criteria established, the following results were obtained: wind energy plants are the most sustainable ones because they appear in three out of all four analyzed scenarios, within acceptable sustainability values; hydroelectric, geothermal, photovoltaic, natural gas, photothermal and heavy oil plants are sustainably acceptable because they appear in two scenarios and

Table 5
Global sustainability result for all analyzed plants, according to the median of all values.

	Plant	**Repetitions**
Acceptable (values above the median)	Wind energy	3
	Hydroelectric	2
	Geothermal	2
	Natural gas	2
	Photovoltaic	2
	Photothermal	2
	Heavy oil	2
	Nuclear	1
	Coal	1

finally, nuclear and coal plants are not advisable, as shown in Table 5.

7. Conclusions

The methodology proposed to assess all four dimensions of sustainability for electric power plants, using Espinoza's environmental evaluation method and the AHP multicriteria method, in the framework of LCA, for four scenarios, ranks and delivers results that can be justified according to the subjectivity of each evaluator. The use of the statistical value of the median provides the global sustainability assessment.

The most affected environmental subjects in analyzed plants, currently operated by CFE in the four proposed scenarios by life cycle stage, are:

- *during construction*: biodiversity;
- *during operation*: biodiversity and air; and
- *during decommission*: for the hydroelectric plant, soil and biodiversity, and for all other plants, water.

Environmental subjects showing the most environmental effects for analyzed plants, currently operated by CFE, in all four proposed scenarios by plant, are:

- *hydroelectric*: soil;
- *thermoelectric*: air;
- *geothermal and nuclear*: biodiversity; and
- *wind energy*: soil.

Throughout the life cycle by scenario, in Mexico, wind energy plants are the most sustainable ones. According to sustainability results throughout the whole life cycle, we can assert that the most advisable power plant is the wind energy plant, and nuclear and coal plants are the less advisable, under the current conditions in Mexico.

These results imply that, in order to achieve a sustainable energy development in Mexico, the use of renewable energies must be strongly supported.

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